TURBULENCE MEASUREMENTS IN TIDAL BORES: INFLUENCE OF BED ROUGHNESS

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Abstract: A positive surge results from a sudden change in flow that increases the depth, and a geophysical application is the tidal bore. Mew experimental investigations were conducted in a rectangular channel and detailed unsteady velocity measurements were performed with high temporal and spatial resolution. The experiments encompassed undular and breaking bores in a horizontal slope and both smooth and rough invert conditions were tested. An undular bore was observed for surge Froude numbers less than 1.5. For Fr < 1.3, the undulations free-surface was smooth. For 1.3 < Fr < 1.45 to 1.5, some breaking was seen at the first wave crest. For Fr > 1.5, a breaking bore was observed. Detailed instantaneous velocity measurements showed a marked effect of the surge front passage. A comparison between undular and weak surge data suggested some basic differences. A systematic comparison was conducted to study the effects of bed roughness. The boundary friction contributed to some wave attenuation and dispersion. The instantaneous velocity data indicated a marked effect of the rough screens on the entire turbulent velocity field.

Keywords: Turbulence, Tidal bores, Physical modelling, Bed roughness, Bore front, Wave attenuation, Turbulent mixing, Sediment processes, Ecology.

INTRODUCTION

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising (Fig. 1). It forms during spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary, where the estuarine zone is defined as a water body where the tide meets a river flow. Scientific studies demonstrated that the arrival of the tidal bore is always associated with intense bed material mixing and with upstream advection of suspended material behind the bore front (TESSIER and TERWINDT 1994, GREB and ARCHER 2007). In the Sélune River, the author observed the formation of a new estuarine channel by the tidal bore on 31 Aug. 2008. The tidal bore cut across a channel meander between Pointe du Grouin du Sud and Roche Torin, and the new incision became the main channel by the flood tide.

To date, a limited number of studies encompassed turbulence measurements (HORNUNG et al. 1995, KOCH and CHANSON 2008,2009). In this study, unsteady turbulence measurements were performed in tidal bores on smooth and rough beds. It is the aim of this work to detail the surge front processes including the unsteady turbulence based upon experimental data obtained in a large size facility under carefully controlled flow conditions. The results provide an unique characterisation of the flow field with a detailed assessment of bed roughness effects.

EXPERIMENTAL FACILITY AND METHODS

New experimental investigations were conducted in a rectangular, horizontal channel (12 m long, 0.5 m wide). The flume had a smooth PVC bed and glass sidewalls, and the waters were supplied by a constant head tank. A tainter gate was located next to the downstream end, and its rapid closure generated a tidal bore propagating upstream against the initially steady flow (Table 1).

The water discharge was measured with orifice meters that were designed based upon the British Standards. The unsteady water depths were measured with a series of Mic+25/IU/TC acoustic displacement meters, spaced along the channel between x = 10.9m and 2 m, where x is the longitudinal distance from the channel upstream end. Detailed unsteady velocity

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measurements were performed with high temporal and spatial resolution (200 Hz, sampling volume: 6×6×1.5 mm^3) using an acoustic Doppler velocimeter Nortek™ Vectrino+ (Serial No. VNO 0436) equipped with a three-dimensional side-looking head. Both the acoustic displacement meters and acoustic Doppler velocimeter sampled simultaneously at 200 Hz and synchronised within 1 ms.
The translation of the ADV probes in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo™ digimatic scale unit. The error on the vertical position of the probe was $\Delta z < 0.025$ mm. The accuracy on the longitudinal position was estimated as $\Delta x <$ +/- 2 mm. The accuracy on the transverse position of the probe was less than 1 mm. Additional information was reported in CHANSON (2008).

(A) Arrival of the tidal bore of the Dordogne River in Saint Pardon, France (22/7/2008)

(B) Tidal bore in the Baie du Mont Saint Michel (19/10/2008)
(C) Tidal bore of the Garonne River at Podensac (27/9/2008)
Fig. 1 - Photographs of tidal bores in natural systems

Bed roughness and inflow conditions
For a series of experiments (Table 1, Series B), the smooth PVC channel bed was covered with rough screens made from plastic electrical lighting louvers with square patterns (16 mm size, 8

mm high). The hydraulic roughness was tested in steady flow conditions in two long channels. The equivalent Darcy friction factor ranged from f_{screen} = 0.05 to 0.08. The result was independent of Reynolds and satisfied:

$$\frac{1}{\sqrt{f_{screen}}} = 0.252 \times \left(\frac{k}{D_H} \right)^{-0.823} \tag{1}$$

where k is the screen height (k = 8 mm) and D_H is the hydraulic diameter.

Detailed velocity distribution measurements were performed in steady flows at x = 5 m. The results are presented in Figure 2 where d_o and V_o are the initial flow depth and velocity, and z is the vertical elevation above the PVC bed (Series A) and above the screens (Series B). The data showed that the flow was partially-developed at x = 5 m while the bed roughness had a marked effect (Fig. 2). Larger turbulent velocity fluctuations were observed above the rough screens, while the vertical distribution of longitudinal velocity exhibited a flatter shape. In the boundary layer flow, the dimensionless turbulent velocity fluctuations were respectively v_y'/v_x' = 0.49 and v_z'/v_x' = 1.3 for both smooth and rough beds. The former result (v_y'/v_x' = 0.49) was in agreement with a previous study in the same channel (v_y'/v_x' = 0.52, KOCH and CHANSON 2009). The v_z'/v_x' data were in apparent contradiction with the literature, and the discrepancy was likely caused by the ejection of large scale vortical structures in the channel intake structure for that particular flow rate.

Table 1- Experimental flow conditions: positive surges in a horizontal channel

Reference (1)	Q (m^3/s) (2)	d_o (m) (3)	Surge type at x = 5 m (4)	U (m) (5)	Fr (6)	Remarks (7)
HORNUNG et al. (1995)	0	--	Undular to breaking	--	1.5 to 6	Smooth bed. L = 24 m.
KOCH and CHANSON (2008,2009)	0.040	0.079	Undular to breaking	0.14 to 0.68	1.31 to 1.93	Smooth PVC bed. L = 12 m, B = 0.5 m.
Present study						
Series A	0.058	0.137	Undular to breaking	0.56 to 0.90	1.17 to 1.49	Smooth PVC bed. L = 12 m, B = 0.5 m.
Series B	0.058	0.142 (*)	Undular to breaking	0.50 to 0.89	1.13 to 1.47	Rough screens (k = 8 mm). L = 12 m, B = 0.5 m.

Notes: d_o: initial depth measured at x = 5 m; Fr: surge Froude number; Q: initial steady flow rate; U: surge front celerity measured at x = 5 m; (*) measured above the screens.

TIDAL BORE PROPAGATION

Several types of positive surges were observed: an undular (non-breaking) bore for surge Froude numbers Fr less than 1.3, an undular surge with some slight breaking for Froude numbers between 1.3 and 1.45 to 1.5, and a breaking surge with a marked roller for Froude number greater than 1.45 to 1.5 (Fig. 3). Herein the surge Froude is defined as $Fr = (V_o + U) / \sqrt{g \times d_o}$ where g is the gravity acceleration and U is the surge front celerity for an observer standing on the bank, positive upstream.

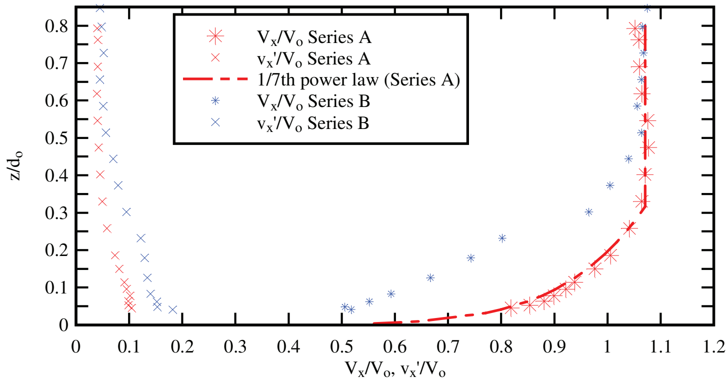
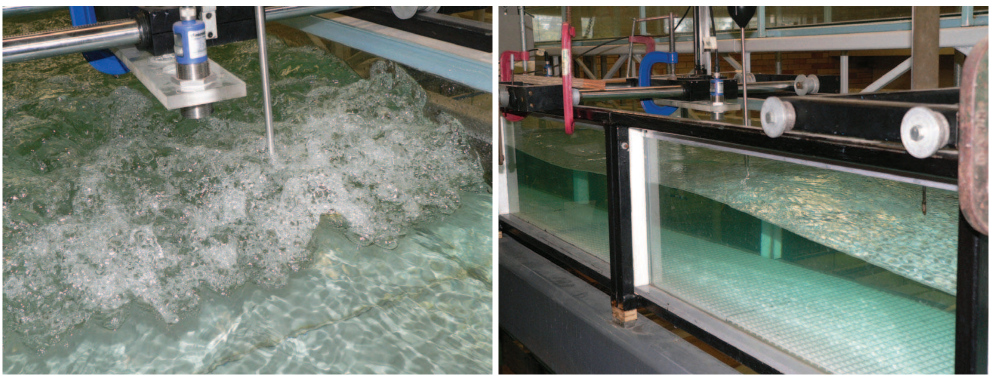


Fig. 2 - Steady flow velocity distributions at x = 5 m - Comparison between smooth and rough bed configurations: Q = 0.058 m^3/s, d_o = 0.137 m, δ/d_o = 0.32 (Series A); Q = 0.058 m^3/s, d_o = 0.142 m, δ/d_o = 0.48 (Series B)



(A) Breaking surge advancing on the smooth bed, Fr = 1.50, surge front passing the ADV at x = 5 m (shutter speed: 1/80 s)
(B) Undular surge propagating on the rough screens, Fr = 1.20, Passage of the first wave crest at x ~ 4.5 m (shutter speed: 1/80 s) - Surge propagation from left to right
Fig. 3 - Photographs of the tidal bore experiments on smooth and rough inverts

For small surge Froude numbers (Fr < 1.3), the bore propagated upstream relatively slowly and the positive surge consisted of a train of well-formed undulations. The free-surface undulations had a smooth appearance and no wave breaking wave observed (Fig 3B). For intermediate surge Froude numbers (1.3 < Fr < 1.45 to 1.5), some wave breaking was observed at the bore front, and the ensuing free-surface undulations were flatter. At large surge Froude numbers (Fr > 1.45 to 1.5), a breaking bore was observed (Fig. 3A). The surge front propagated relatively rapidly, and the free-surface appeared to be quasi-two-dimensional. For the entire range of investigations, the bore celerity U increased from 0.5 to 0.9 m/s with increasing Froude number. The basic flow patterns were identical for both smooth invert and rough screens.

Wave attenuation and effect of boundary friction on undular positive surges

For sinusoidal deep-water waves, IPPEN and KULIN (1957) developed an estimate for the wave amplitude attenuation due to boundary friction as

$$\frac{\Delta d/d}{(\Delta d/d)_{x=x_o}} = \left(1 + \frac{2}{15} \times f \times \frac{(x_o - x)/d}{\Delta d/d}\right)^{-1} \qquad (1)$$

where Δd is the attenuated positive wave height at a distance (x_o-x) from the reference location x_o where the wave height is $\Delta d_{x=xo}$, d is the water depth and f is the Darcy-Weisbach friction factor. In the present study, the undular (non-breaking) bore propagation data showed some attenuation of the wave height Δd with the increasing distance of propagation. On the smooth bed, the wave attenuation was about 10% over a 8.5 m long distance. On the rough screens, the wave attenuation was nearly 70% along the same distance for Fr = 1.2, but it decreased drastically for larger surge Froude numbers. A different reasoning may derive from the Saint-Venant equations (HENDERSON 1966, CHANSON 2004). The flow resistance delays the surge formation for $V_o/\sqrt{g \times d_o} < 2$, and makes the positive surge more dispersive. Yet neither Equation (1) nor the Saint-Venant equation considerations can explain the observed effect of the surge Froude number on the lesser undular wave attenuation at larger Froude numbers.

The wave period and wave length data were compared with the wave dispersion theory for gravity waves in intermediate water depths. For wave propagation in presence of an initial current (velocity V_o positive downstream), the linear wave theory yields a dispersion relationship between the angular frequency $2\times\pi/T$ and wave number $2\times\pi/L_w$ (NIELSEN 2009). For the free-surface undulations of an undular surge propagating against a current, it yields:

$$\frac{2\times\pi}{T}+\frac{2\times\pi\times V_o}{L_w}=\sqrt{\frac{2\times\pi\times g}{L_w}\times\tanh\left(\frac{2\times\pi\times d_{conj}}{L_w}\right)} \qquad (2)$$

where L_w is the wave length, T is the wave period as seen by an observed fixed on the bank and d_{conj} is the conjugate depth. (The conjugate depth represents the average water depth along a wave length.). Equation (2) is compared with the experimental data in Figure 4. The data showed close results between smooth and rough bed data, and Equation (2), although it must be stressed that Equation (2) is not truly applicable to an undular bore propagation.

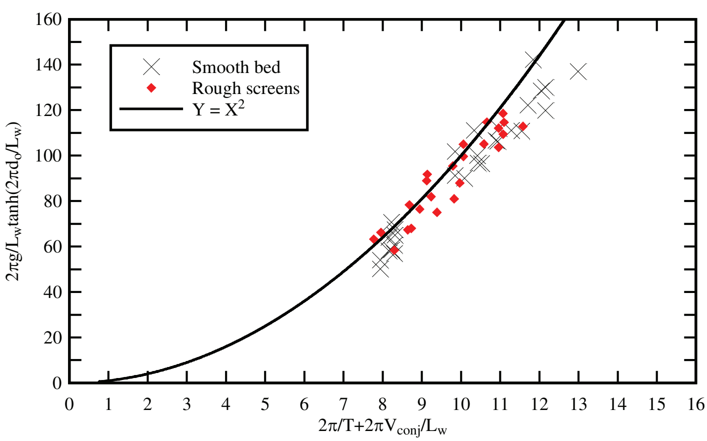
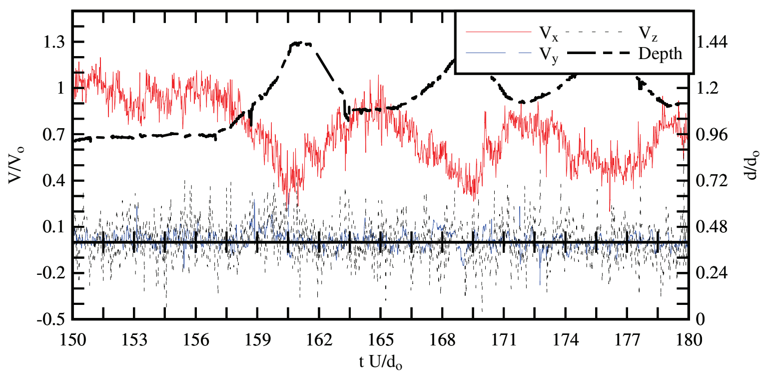


Fig. 4 - Wave dispersion in undular tidal bore propagating on smooth and rough bed - Comparison with the theoretical solution of gravity wave dispersion (Eq. (2))

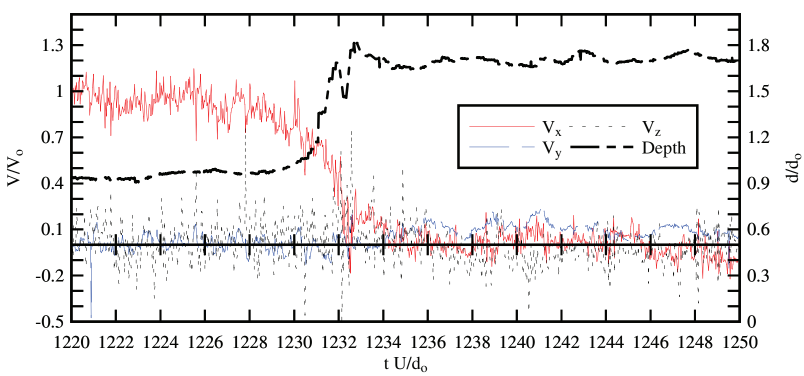
UNSTEADY TURBULENT VELOCITY MEASUREMENTS

Detailed velocity measurements were conducted for two surge Froude numbers: Fr = 1.2 & 1.5 on both smooth bed and rough screen invert with an identical initial flow rate Q = 0.058 m^3/s. The turbulent velocity measurements were conducted at x = 5 m at several vertical elevations with $z/d_o < 0.85$, for the ADV sampling volume and ADV receivers to be underwater prior to and during the bore front passage.

The instantaneous velocity measurements showed that the tidal bore passage was associated with a rapid flow deceleration as shown by KOCH and CHANSON (2009). The longitudinal velocity component decreased rapidly when the bore front passed above the sampling volume (Fig. 5). Afterwards, the longitudinal velocity was typically positive at all vertical elevations. The instantaneous velocity measurements demonstrated however some major differences in longitudinal velocity redistribution between the undular and breaking surges. The undular (non-breaking) surge was characterised by a train of secondary waves, or free-surface undulations, following the first wave crest. When the undular bore front passed the sampling point, a relatively gentle longitudinal flow deceleration was noted at all vertical elevations (Fig. 5A). The longitudinal velocity component was minimum beneath the first wave crest and it oscillated afterwards with the same period as the surface undulations and out of phase. The vertical velocity data presented a similar oscillating pattern beneath the free-surface undulations with the same periodicity, but out of phase. The data trends were consistent with the irrotational flow theory (ROUSE 1938, CHANSON 2009).



(A) Undular bore: d_o = 0.1385 m, V_o = 0.830 m/s, U = 0.553 m/s, Fr = 1.17



(B) Breaking bore: d_o = 0.1388 m, V_o = 0.832 m/s, U = 0.903 m/s, Fr = 1.50

Fig. 5 - Instantaneous turbulent velocity measurements on smooth bed at z/d_o = 0.150

In contrast, a breaking bore exhibited a sharp front with a marked roller and some bubble entrainment. The free-surface was curved upwards immediately prior to the roller toe (Fig. 5B). The gentle rise of the free-surface was linked with a gradual decrease of the longitudinal velocity component at all vertical elevations as shown by HORNUNG et al. (1995) and KOCH and CHANSON (2009). The roller passage corresponded to a rapid decrease of the longitudinal velocity component. The flow deceleration was notably sharper than that for an undular bore all relative elevation z/d_o. For example, let us compare Figures 5A and 5B for z/d_o = 0.15. In the breaking bore, the velocity data showed a further distinctive feature. For $z/d_o < 0.2$, the longitudinal velocity became negative although for a short duration highlighting a relatively rapid transient associated with unsteady flow separation. This flow feature was first reported by KOCH and CHANSON (2009) and investigated numerically by FURUYAMA and CHANSON (2008).

Effect of bed roughness

The effects of bed roughness were tested for both undular (non-breaking) and breaking bores. The experimental data showed that the rough invert had a significant effect on the flow field. The initial flow exhibited higher turbulence levels, and the flow field during and after the surge front passage remained highly turbulent.

For an undular bore, the bed roughness induced a strong attenuation of the oscillating free-surface flow pattern effect on the longitudinal and vertical velocity components for $z/d_o < 0.2$, although it was still seen for $z/d_o > 0.5$. With the breaking bore, the longitudinal velocity data indicated a longer transient recirculation for $z/d_o < 0.2$ on the rough screens (Fig. 6). Such a recirculation pattern is sketched in Figure 7. In the recirculation region, large negative longitudinal velocities were observed: $V_x/V_o \sim -0.3$ to -0.5 in average. The transient event lasted at least 3 seconds. Its precise duration could not be recorded because the data collection was stopped as soon as the surge front reached the upstream channel end (x = 0).

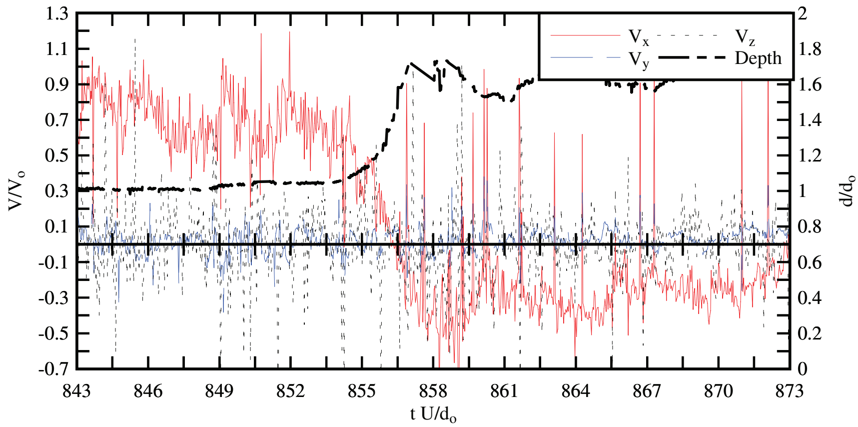


Fig. 6 - Instantaneous turbulent velocity measurements on rough bed: breaking bore: $d_o = 0.1415$ m, $V_o = 0.824$ m/s, U = 0.892 m/s, Fr = 1.46, $z/d_o = 0.179$

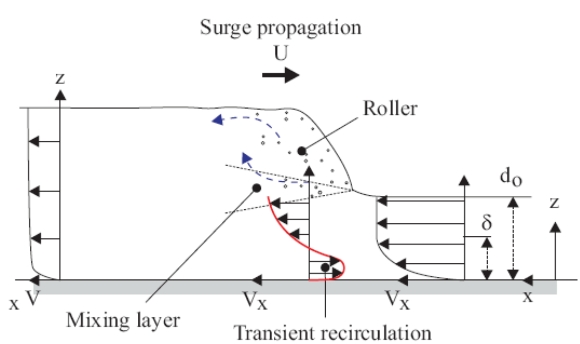


Fig. 7 - Sketch of the transient recirculation beneath a breaking surge above a rough invert

CONCLUSION

A tidal bore is a sudden change in flow that increases the depth observed in estuaries when the tidal flow turns to rising (Fig. 1). New experimental investigations were conducted in a large rectangular channel on smooth and rough invert. Detailed velocity measurements were performed with a high temporal and spatial resolution and the free-surface elevations were recorded using non-intrusive acoustic displacement meters.

An undular (non-breaking) bore was observed for surge Froude number Fr less than 1.3. For 1.3 < Fr < 1.45 to 1.5, some breaking was seen at the first wave crest. For surge Froude numbers greater than 1.5, a breaking bore was observed with a marked roller, although some surface upward curvature ahead of the roller was observed with the range of investigations. Detailed instantaneous velocity measurements showed a marked effect of the surge front passage. The longitudinal velocities were characterised by a rapid flow deceleration at all vertical elevations, and large fluctuations of all velocity components were recorded beneath the surge and whelps.

The boundary friction contributed to some wave attenuation and dispersion, and the free-surface data showed some agreement with the wave dispersion theory for intermediate gravity waves. The instantaneous velocity data indicated a marked effect of the rough screens on the turbulent velocity field. Larger turbulent velocity fluctuations were observed on the rough screen invert. In an undular bore, the time-variations of the longitudinal velocity exhibited a lesser oscillating pattern than on a smooth bed close to the bed ($z/d_o < 0.2$). In a breaking surge, a relatively longer transient recirculation was observed next to the invert.

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